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The influence of incorporating a forecutter on the performance of offshore pipeline ploughs

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ABSTRACT

Installation of offshore pipelines in the seabed can be efficiently achieved using pipeline ploughs. Increased efficiency may be achievable through incorporating a smaller forecutter in advance of the main plough share. Currently guidance is limited and conflicting as to the advantages or disadvantages of incorporating a forecutter. To investigate the effect of forecutter inclusion model tests were undertaken at 1/50th scale under laboratory conditions in sand beds prepared at different relative densities in both dry and saturated conditions. Dry sand tests were used to determine the effect of the forecutter on the static or passive components of plough tow force. The currently adopted passive pressure coefficient (C_s) did not appear to vary with relative density to the same degree as previously suggested and the forecutter increased the magnitude of the passive or static resistance to ploughing. Saturated tests were used to determine the effects of the forecutter on the rate dependant component of ploughing resistance and allow verification of a dimensionless form of rate effect representation. The forecutter acts to reduce the rate effect component of plough tow force in both fine sand (low permeability) and to a lesser extent in medium sand (higher permeability). In fine and silty sands, however, incorporating a forecutter would seem highly beneficial at all ploughing depths and soil densities but in medium sand (higher permeability) the benefits of incorporation are limited to an operating window at shallower trench depths and lower relative density.

1. Introduction

Offshore oil and gas pipelines are often buried below the sea bed to typical depths of 1.2–2 m. This provides a means of protection from fishing activities and hydrodynamic loading. If the pipeline is subsequently backfilled upheaval buckling due to thermal expansion on commissioning can be prevented. Backfilling also gives increased thermal insulation which allows the pipeline product to flow more efficiently [1]. One of the most common means of pipeline burial is to use a pipeline plough (Fig. 1) towed along the sea bed by a support vessel. Pipeline ploughs use a wedge-shaped blade known as a share to cut the soil thus forming a trench. The forces anticipated during ploughing are typically assumed to be derived from interface friction between the plough and the soil, a passive force component due to the shearing resistance of the soil and a 'rate effect' component [2]. The rate effect is significant in fine and silty sands and arises because soil shearing at typical ploughing velocities results in a partially drained soil response [3]. During shearing, and subsequent dilation of the soil, water is drawn into the dilation zones under a pressure differential. As the rate of shearing increases so does the corresponding pore pressure reduction with an associated increase in effective stresses and therefore shear stress. The rate effect defines the magnitude of increase in shearing resistance with increase in velocity. The rate effect can increase tow forces to a level whereby ploughing occurs at an uneconomically slow rate [3].

In an attempt to reduce the rate effect, ploughs may be fabricated with a forecutter mounted onto the beam of the plough, in front of the share (Fig. 1). The forecutter is typically smaller than the share and is designed to produce a shallow trench (depth, D_f) in the sand which the share then deepens and opens up. It is thought that the forecutter reduces the rate effect by splitting the depth of the total trench (D_t) which effectively reduces the drainage path length required to allow pressure equalisation. However, there is currently little evidence to support this assumption. Hata [4] recognised that reducing the rate effect by increasing the number of blades or shares was unfortunately offset by the extra plough weight. Van Rhee and Steeghs [5] investigated the potential benefits of a multi-blade plough by conducting tests which involved making multiple passes with a single bladed plough (each successive pass deeper than the last) to simulate

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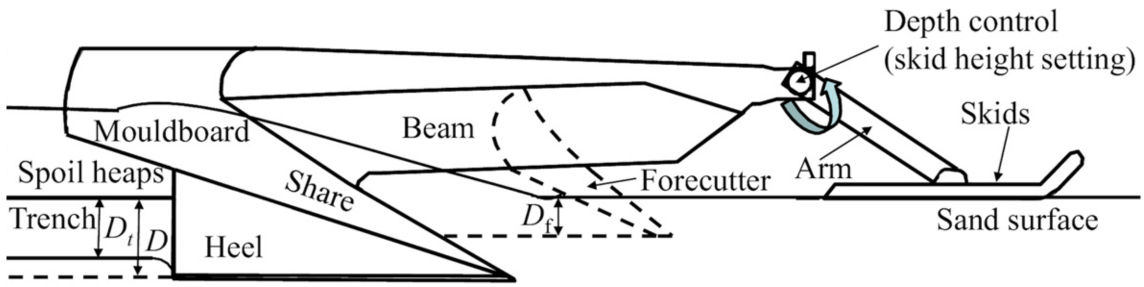

Fig. 1. Schematic of model pipeline plough with forecutter shown during trenching.

a multi-bladed plough. In contrast to the findings of Hata [4], van Rhee and Steeghs [5] found that a multi-bladed plough offered no benefit in terms of rate effects over that of a single bladed plough. It is, however, unclear whether van Rhee and Steeghs [5] make any account for interface friction when summing the forces of various passes to simulate a multi-blade plough.

Current predictions of the ploughing tow forces (F) and plough advance rates (or velocity, v) are typically based upon the experience of operators in certain soil conditions or they may use the widely adopted empirical model developed by Cathie and Wintgens [2].

$$F = C_w W' + C_s \gamma' D^3 + C_d v D^2 \tag{1}$$

where C_w is a dimensionless friction coefficient, W' is the submerged buoyant plough weight, C_s is a dimensionless passive pressure coefficient, γ' is the submerged unit weight of the soil, D is the depth from the original sand surface to the heel of the plough main share and C_d (t/m^3/h) is a dynamic or rate effect coefficient which unfortunately is not dimensionless. The values used for the three coefficients were originally selected from data obtained from variable natural soil conditions in an environment where accurate and precise observations are very difficult. For example, it is recommended that in situ testing (or sampling) that may be used to determine soil type and characterisation is typically undertaken at 0.5–1 km intervals making it difficult to correlate actual plough behaviour with soil type [6]. Unfortunately, the Cathie and Wintgens [2] approach does not distinguish between the use of ploughs with or without forecutters.

As a result of the conflicting reports regarding the performance of ploughs with forecutters, and the lack of information for tow force and velocity predictions when using ploughs with forecutters, research was undertaken to investigate the influence of a forecutter on the performance of offshore pipeline ploughs. This paper presents the findings of a laboratory-based investigation into the performance of incorporating a forecutter during ploughing. Testing was undertaken in different permeability sands prepared at different relative densities (D_r) with pore pressures measured beneath the share during some of these tests. The results of the study show that incorporating a forecutter may be beneficial in some circumstances but not in others. The performance of dimensionless form of rate effect correction is also verified against the model testing.

2. Experimental techniques

Scale model ploughing tests were conducted using a 50th scale model plough based on CTC Marine's advanced pipeline plough (APP) the mass of which was scaled down by 50^3 and all lengths by 50. The model plough was manufactured with a detachable forecutter which allowed its influence over plough behaviour to be investigated directly [7]. Additional reference is made to similar testing carried out at 25th and 10th scale which is described by Lauder [7].

2.1. Model ploughing setup

The testing apparatus and experimental setup is shown in Fig. 2. Tests were undertaken in a 2 m long by 0.5 m deep by 0.5 m wide tank. A 20 kg capacity model RLT load cell, mounted on a carriage was connected to the plough via a tow wire and used to measure the tow force during ploughing. The pitch of the plough was measured by a clinometer mounted on its beam. A 200 mm stroke linear variable differential transformer (LVDT) was used to measure the depth of the plough and was mounted on the carriage. A draw wire transducer (DWT) was used to measure the horizontal displacement of the carriage and to allow determination of plough displacement. During a test the carriage was pulled forwards by a second tow line connected to a winch at the opposite end of the tank. Two miniature Druck pore pressure transducers (PPTs, type: PDCR 81) were placed in the sand along the centreline of the plough's projected run to investigate the effect of forecutter installation on pore pressure development. The transducers were placed at 1000 mm from the DWT end of the box (Fig. 2) and approximately 30 and 60 mm below the anticipated share depth.

In order to allow the effect of forecutter inclusion to be studied in different soil types three sands of different grading were prepared at different densities. Test beds were prepared at a range of relative densities by dry pluviation from a slot pluviator translated above the sand surface with a constant drop height of 800 mm. This allowed test beds to be prepared at relative densities of 50% and upwards. To produce loose beds in dry sand repeatable beds were prepared purely by stirring the sand with a steel rod. Pluviation or stirring was followed by levelling of the final surface of the sand by scraping it flat. For saturated tests the sample was then saturated slowly with water through a hose attachment to the tank which entered via a gravel base drainage layer. Tests were conducted in three different siliceous sands: medium sand (HST50), fine sand (HST95) and silty-sand (Redhill110). Further detail is given in Table 1. Permeability of the sand was determined using a constant head permeability test in accordance with BS1377 [8]. Direct shear box tests were undertaken using a standard 60 mm square shear box to BS1377 [8] on dry sand/sand samples. The one-dimensional Young's modulus (E'_0) required to derive the coefficient of consolidation was determined from oedometer testing [7]. Normal stresses employed during testing covered a wide range from 0.3 to 70 kPa with the lower stresses chosen to reflect shallow plough burial in the model tests. Similar testing was undertaken for the sand/steel interface, in which the lower half of the shear box was replaced by a solid steel block of similar surface roughness to the plough surfaces. In both series of tests the sand was prepared at relative densities designed to mimic those used during the model testing programme. Sand samples were sheared at a constant rate of 1.2 mm/min. Further detailed information on soil characterisation is described in Lauder [7].

Once the test bed had been prepared, the plough was placed on the surface of the sand (Fig. 2) and connected to the tow wire. The LVDT

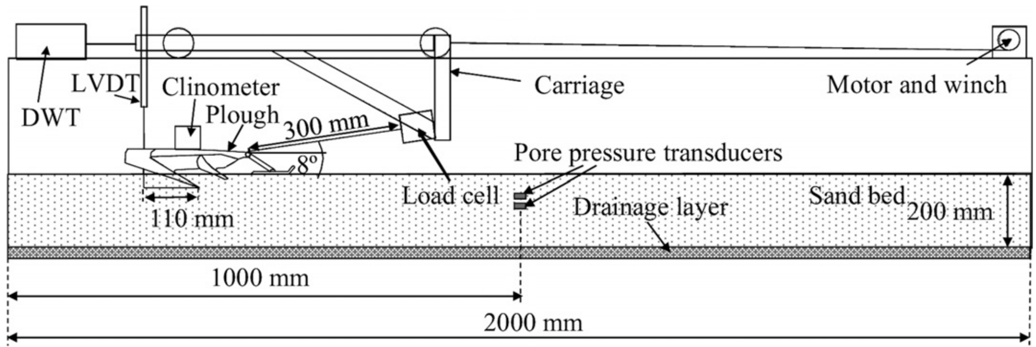

Fig. 2. Model plough test apparatus with dimensions shown at model scale.

Table 1
Summary of the physical properties of the three sands tested.

Property	Sand		
	HST50	HST95	Redhill110
Grading description	Medium sand	Fine sand	Silty sand
Permeability, k[a] (m/s)	4.95×10^{-4} (25%)	1.23×10^{-4} (17%)	1.01×10^{-4} (30%)
One dimensional Young's modulus, E'_0[b] (kN/m^2)	824 (61%)	647 (53%)	600 (44%)
D_{10} [c] (mm)	0.19	0.10	0.08
D_{50} (mm)	0.25	0.14	0.12
Critical state friction angle[c,d], φ'_{crit}(°)	34	32	34
Critical state interface friction angle, δ'_{crit} (°)	27	24	–
Maximum dry density, ρ_{max} (kg/m^3)	1765	1792	1628
Minimum dry density, ρ_{min} (kg/m^3)	1535	1487	1295

[a] Permeability and E'_0 shown with relative density of sample in parenthesis.
[b] E'_0 determined at effective stresses relevant to model testing (0.2–0.3 kN/m^2).
[c] Particle size at 10% passing from particle size distribution determination.
[d] Friction angles determined at normal stresses from 0.2 to 70 kPa.

was then lowered onto the plough and the motor switched on to initiate the winch. The 2 m long tank gave the 250 mm long plough 1400 mm of travel to achieve steady state ploughing conditions. The high torque winching system allowed constant plough velocities between 20 m/h and 400 m/h to be used in the investigation. Plough testing during this study was typically undertaken at speeds varying from 40 to 200 m/h in the 50th scale tests in addition Lauder [7] undertook 25th scale tests at 40–340 m/h which are presented for comparison purposes. These speeds were chosen to reflect typical field ploughing speeds between 150 and 300 m/h, but it is acknowledged that extremes of speeds from close to zero to 560 m/h may occur [2]. All of the instrumentation was monitored using a USB data acquisition system with data sampling at 1 s intervals. Further information on the experimental setup and its development can be found in Brown et al. [9], Bransby et al. [10] and Lauder [7].

2.2. Establishing steady state ploughing conditions

At the start of a ploughing test the plough sits on the surface of the sand with the share usually embedded a few millimetres. As the plough is towed forwards it starts to penetrate into the sand to a depth determined by the height of the skids relative to the share. Fig. 3 shows the development of plough depth and tow force during a test. The plough starts with the share penetrating 4 mm into the sand and as the test progresses its depth reaches 42 mm by around 600 mm horizontal displacement. From this point onwards the depth stabilises and no further significant depth change occurs for the rest of the test. The tow wire is slack at the start of the test and the tow force, therefore, starts at 0 N. The tow force quickly reaches approximately 5 N once the test is started and from then it gradually increases to approximately 19 N at 600 mm horizontal displacement (5.45 share lengths) where it stabilises and reaches a 'steady state' during which

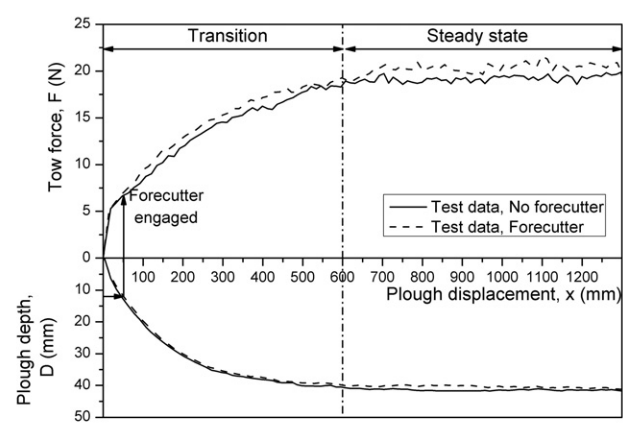

Fig. 3. Variation of model plough depth and tow force with displacement during tests in dry loose fine sand (HST95).

no further significant change takes place. In subsequent figures where tow force and depth are shown summarised for several tests, the values used are average values derived from the "steady state" from 600 mm displacement to the end of the test. Fig. 3 shows typical results compared in dry sand where the plough has been used both with and without a forecutter.

3. Forecutter effects on ploughing in dry sand

Initial tests were undertaken in dry sand to allow the interface friction components and passive force components of plough resistance to be decoupled from the rate effect components (Eq. (1)).

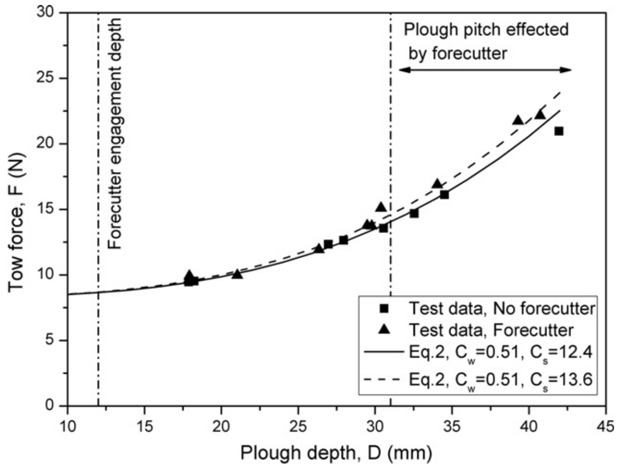

Fig. 4. Effect of forecutter on model plough tow forces in loose dry HST50 ($D_r = 25\%$).

3.1. Forecutter effects on static plough resistance components

Fig. 4 shows how the steady-state tow forces against plough depth for ploughing tests both with and without a forecutter. As the tests are being undertaken in dry sand Eq. (1) for tow force prediction has been reduced to:

$$F = C_w W' + C_s \gamma' D^3 \tag{2}$$

To aid distinction between the data sets Eq. (2) has been used to generate a tow force–depth relationship using parameters appropriate to the ploughing configuration. It appears that the forecutter affects the measured tow forces at relatively shallow depths after it has engaged or comes in contact with the sand (12 mm plough depth). This is also seen in the separation in tow forces measured in Fig. 3 where the tow force for the forecutter case becomes higher than the non-forecutter case at approximately 12 mm plough penetration (0.6 m at prototype scale). This increase may be due to shearing of some sand twice, firstly by the forecutter and secondly by the share as the forecutter does not push sand away from the share's path (see Fig. 1 for relative positions of share and forecutter).

3.2. Forecutter effects on plough attitude

The forecutter also affects plough pitch and causes the plough to pitch forwards for depths where it is engaged with the sand, i.e. $D > 17.5$ mm (Fig. 5). There is also an apparent difference in the pitch with the forecutter at depths greater than 31 mm (Fig. 5, line 2). The forecutter may be increasing forward pitch by altering the moment equilibrium of the plough as the resultant force from the sand above the share and forecutter is pushed forwards towards the skids.

3.3. Modifications to analysis for forecutter inclusion

In the "static" case or when the sand is dry the magnitude of the passive pressure coefficient (C_s) can be determined for both the forecutter and non-forecutter cases. The value of $C_w = 0.51$ is assumed based upon a measured sand interface friction angle (δ) of 27° (where C_w is assumed to correspond to an interface friction ratio similar to tan δ). It should be noted that Cathie and Wintgens [2] recommend a single value of 0.4 (in all cases) for C_w but the value will be influenced by the interface friction angle between the soil and the plough and will vary with soil type, density (to a much lesser extent) and plough surface roughness. A summary of the effect of the forecutter on C_s is shown in Fig. 6 and Table 2.

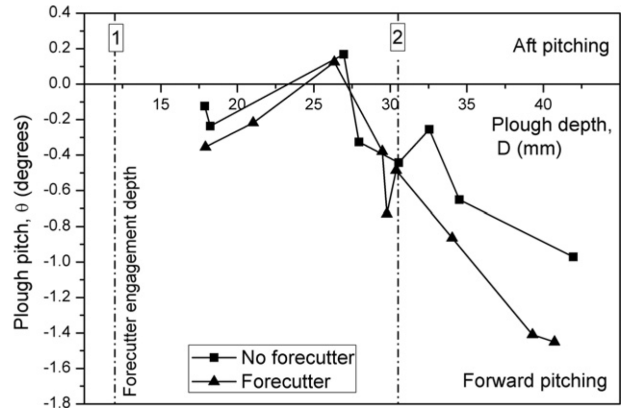

Fig. 5. Effect of forecutter on pitch in loose dry medium sand (HST50, $D_r = 25\%$).

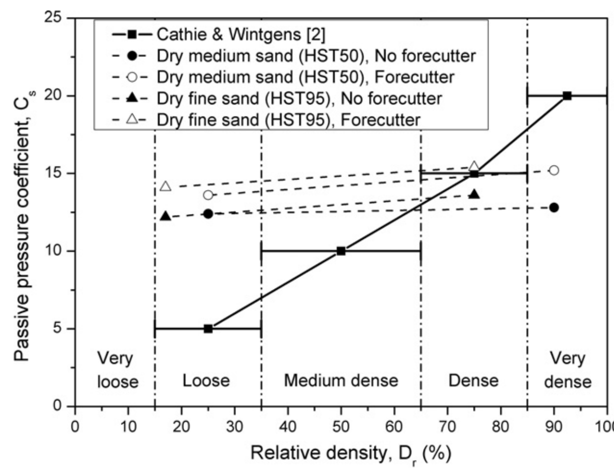

Fig. 6. Comparison of C_s values from model tests in dry and saturated sands compared with Cathie and Wintgens [2] guidance values.

The two things that are apparent from Fig. 6 and Table 2 are that C_s does not appear to vary with relative density to the degree recommended by Cathie and Wintgens [2]. Also the forecutter increases the magnitude of the C_s term which reflects an increase in the passive resistance to ploughing shown in Figs. 3 and 4.

In order to verify that the observed modifications to C_s were not purely a result of model scaling issues a series of additional tests were undertaken using 25th and 10th scale ploughs. Further detail of the testing apparatus required for larger plough testing is given by Lauder [7].

Fig. 7 shows model test results which have been scaled to prototype scale as discussed earlier. If scaling issues were sufficient to influence the test results it might be expected that the highest scaled tow forces would result from the 50th scale tests and the lowest from the 10th scale tests. The data, however, are in reasonable agreement and there is no apparent evidence of scaling issue between the data sets. Significant variation of the model results from those derived from field ploughing [2] might suggest issues with the modelling but actually it is the degree of variation of C_s with relative density at field scale that is more unlikely. During model testing, and a series of plane strain plough analogue tests, Lauder [7] noted that advancing the plough caused the formation of a series of passive soil wedges with a characteristic shear plane emanating from the plough tip to the sand surface in advance of the plough. The resulting friction angle over this shear band is assumed to vary such that it is only the leading edge or tip domain that displays a reduction from peak frictional behaviour to critical state over its length [11]. Stone and Wood [12] suggest that this domain is around $176D_{50}$ (where D_{50} refers to mean

Table 2
Passive pressure coefficient, C_s values in loose, dense and very dense dry sand for ploughs with and without a forecutter.

Sand	Plough configuration	C_s Soil state Loose	Dense	Very dense	Increase in tow force[b]
HST50	Forecutter	13.6 (5)[a]	– (15)	15.2 (20)	6.9–19.2%
HST95	Forecutter	14.1 (5)	15.4 (15)	– (20)	5.2–13.2%
HST50	No forecutter	12.4 (5)	– (15)	12.8 (20)	NA
HST95	No forecutter	12.2 (5)	13.6 (15)	– (20)	NA

[a] Values in parenthesis are C_s values recommended by Cathie and Wintgens [2] shown for comparison.
[b] % Increase as a result of incorporating a forecutter over the range of soil densities tested. Note that this value is also depth dependant.

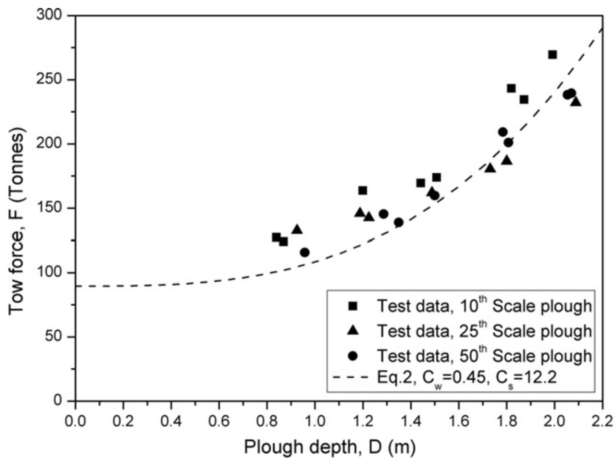

Fig. 7. Variation of tow force with depth for model ploughs without forecutters at 50th, 25th and 10th scale in loose dry medium sand (HST50, $D_r = 17\%$, results shown at prototype scale).

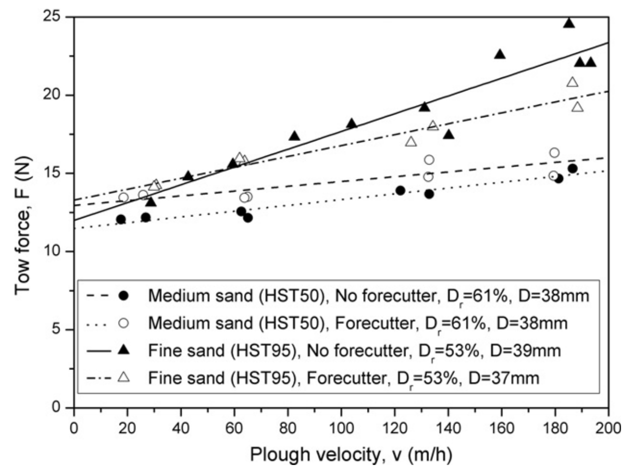

Fig. 8. Comparison of plough performance in fine sand (HST95, $\overline{D}_r = 53\%$) and medium sand (HST50, $\overline{D}_r = 61\%$) both with and without a forecutter (results are shown at model scale).

sand particle size) which for the soils tested here would mean that the tip domain extends from 21 mm (Redhill110) to 44 mm (HST50). For a full scale plough at 1.5 m depth this zone would only reflect 0.7–1.4% of the fully developed shear plane. Thus full scale static plough behaviour is influenced to a greater extent by the critical state friction angle than peak. Therefore, the degree of variation of C_s with relative density presented by Cathie and Wintgens [2] would not be anticipated (Fig. 6).

The near tip domain phenomenon does pose some scaling issues for the model testing but as the length of this zone is controlled by material characteristics it will be the same length in the models and the prototype. Therefore, as the scale of the model ploughs increase the influence of dilation will be reduced. For example, the tip domain would be approximately 32–70% of the shear plane in the 1/50th scale plough reducing to 6–14% at 1/10th scale. Although this may seem significant for the smaller scale tests the tip domain reflects movement from peak to critical state behaviour and is at the leading edge of the forming shear plane. Therefore, as the shear plane is at its full length the tip domain is at very shallow depths and effective stresses. Therefore, the additional contribution of shear stress associated with the tip domain is relatively small. Although this contribution is small it may result in elevated C_s values being derived from the model tests in dense soils which would give conservative values for field application.

It is worth noting that the C_s in loose soils recommended by Cathie and Wintgens [2] appear to be based upon a single site where they describe the data as poor. In fact 8 out of the 18 sites used to determine parameters for ploughing in sand were described as poor by the authors [2]. In terms of this study it is clear that incorporating a forecutter leads to an increase in the "static" force component of between 5 and 19% depending on relative density, plough depth and soil type.

4. Forecutter effects on ploughing in saturated sand

4.1. Forecutter effects on rate dependant plough resistance components

Steady state tow force values are shown in Fig. 8 for ploughing tests in fine (HST95) and medium (HST50) sands prepared at medium density. Linear fits to the data sets are shown to aid understanding, but are not used to derive rate dependant parameters due to slight variations in depths between tests. It is clear that the forecutter causes an increase in tow force at low plough velocities in both sands. This is consistent with the increase in passive pressure component seen in the dry sand. The forecutter also reduces the rate effect in both HST95 and HST50. Fig. 8 shows that although the rate effect is reduced in the lower permeability sand (HST95) there is no benefit in forecutter inclusion until speeds above 60 m/h. At 200 m/h the benefit of inclusion is approximately 15% in terms of tow force reduction. In contrast in the higher permeability soil (HST50) where the rate effects are less significant the inclusion of the forecutter reduces the rate effect but increases the overall tow force to an extent that inclusion has a negative effect over the range of velocities investigated. This is because the increase in the static component of tow force is larger than the reduction of the rate effect at the depth of testing. This suggests that the use of forecutters may not be beneficial in higher permeability soils but as this will also be a function of plough depth a general statement based upon permeability alone cannot be made.

4.2. Forecutter effects on rate dependant plough resistance components

In order to derive the empirical form of dynamic rate effect coefficient C_d from the model scale data it is necessary to scale the results to prototype dimensions (full scale) as the C_d parameter is typically presented in units of tonnes/m^3/h. As the model tests were undertaken

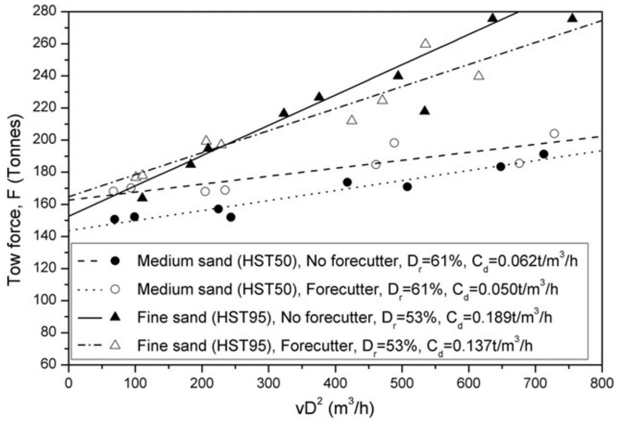

Fig. 9. Determination of dynamic rate effect coefficient C_d for HST95 ($D_r = 53\%$) and HST50 ($D_r = 61\%$) both with and without a forecutter (results are presented at prototype scale).

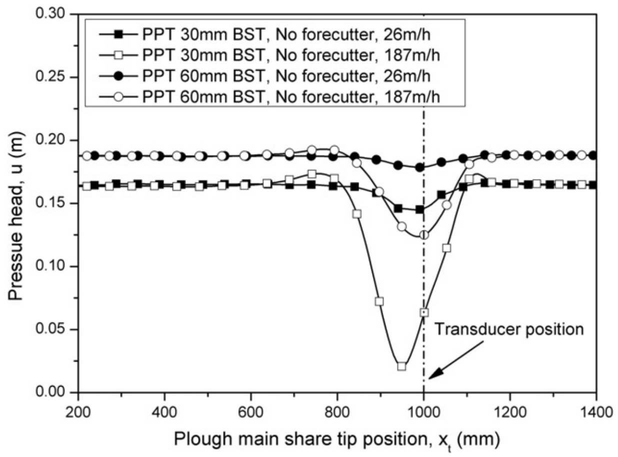

Fig. 10. The change in pore pressure below the share as the plough shears the sand above (loose silty sand, Redhill110, test shown without forecutter, BST = below share tip).

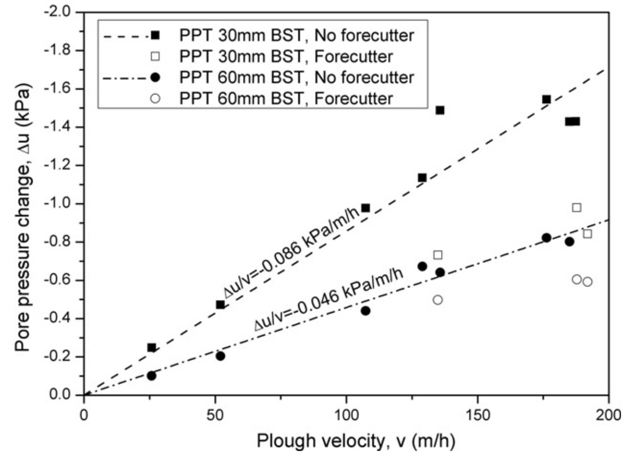

Fig. 11. Maximum reduction in pore water pressure measured during ploughing tests in Redhill110 ($D_r = 41\%$) by pore water transducers at 30 mm and 60 mm below the share.

at 1/50th scale plough depth (D) must be multiplied by a factor of 50 and tow forces by a factor of 50^3. The velocity was not scaled as this was found not to be required [9,13]. The results shown in Fig. 9 are those presented in Fig. 8 but at full scale. As noted above, slight variation may occur during comparative rate effect tests predominantly in terms of trench depth. To allow accurate determination of C_d, tow force is shown plotted against vD^2. A dimensionless representation of the rate effect behaviour is explored later in the paper.

4.3. Sand bed monitoring to investigate forecutter effects

In order to gain insights into the mode of action of the forecutter a limited number of pore pressure transducers were installed in the sand bed in advance of the plough. The results of monitoring the sand bed pore pressures during ploughing are shown in Fig. 10. The figure shows the pore pressures as the plough approaches and then passes over the transducers.

At the higher ploughing rate the pore pressure transducers (PPTs) appear to pre-sense the approach of the plough with a slight increase in pore pressure 587–592 mm (3.8–3.7 share lengths) before the plough arrives at their position. This is followed by a reduction in pore pressure (and subsequent increase in effective stress) as the plough approaches the transducer position with the lowest pressures being reached before the share is above the transducer position. It is apparent that the magnitude of the pore pressure reduction increases with increasing plough speed which supports the measured rate effects. Again the greatest pore pressure reductions occur before the plough has reached the PPT positions (0.46 share lengths for the greatest reduction).

The maximum reduction in pore water pressure for each test is shown against plough velocity in Fig. 11. The magnitude of the pore pressure reduction appears to increase linearly with velocity, similar to the rate effect seen in Figs. 8 and 9. Tests where the forecutter was attached to the plough reveal that the forecutter significantly reduces the degree of pressure reduction below the share (Fig. 11). This in turn will reduce the effective stress in the soil in advance of the plough making it easier to shear the soil. This may be as a result of the forecutter ploughing the soil at a shallower depth leading to a reduction in the drainage path length to the main share and thus allowing more rapid equalisation of the pore pressures in advance of the plough. The forecutter effectively reduces the change in pore pressure by approximately 50% at 30 mm below the plough whereas the effect is less marked at 60 mm below the plough.

5. Parametric study to identify scenarios for beneficial forecutter inclusion

From the evidence presented from model testing it is apparent that the decision whether or not to incorporate a forecutter needs to be made taking into account both the passive and velocity dependant components of plough resistance. From an operator perspective it is necessary to be able to predict ploughing progress rates at the contract trench depth and vessel towing capabilities. To allow this to occur specific C_s and C_d values are required that reflect ploughing performance when a forecutter is incorporated (Figs. 6 and 12).

5.1. Modification of rate parameters for forecutter inclusion

Fig. 12 is based upon the relationship proposed between sand permeability and the rate effect term (C_d) by Cathie and Wintgens [2]. The D_{10} value from the particle size distribution is used to reflect soil permeability [14]. As the approach of using D_{10} (mm) to reflect permeability does not allow for the degree of particle packing, contours at various relative densities were developed [2] which are shown in Fig. 12. The average values of C_d (t/m^3/h) determined from the model testing series in the three soils are shown in Fig. 12. These values were derived using Eq. (1) with appropriate values of C_w and C_s as previously determined for both the forecutter and no forecutter case.

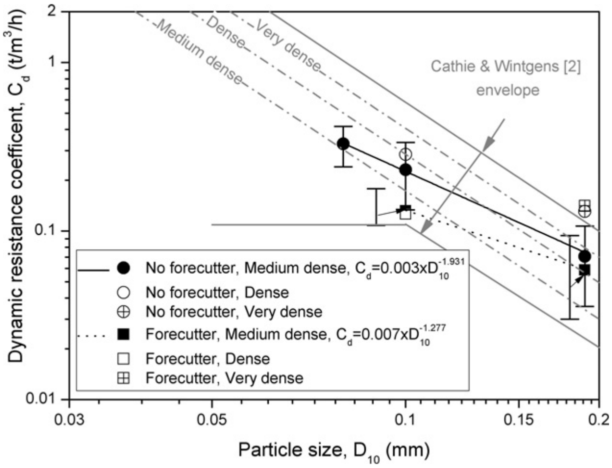

Fig. 12. Average C_d values from tests at various relative densities both with and without a forecutter (for clarity error bars represent data range shown only for medium density tests and shown offset for forecutter case).

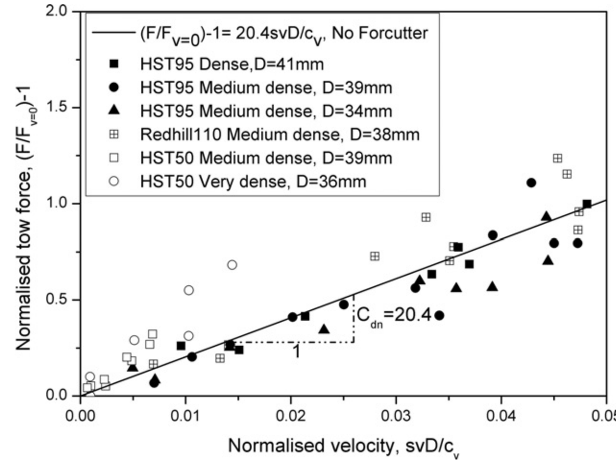

Fig. 13. Dimensionless form of the rate effect behaviour shown for the no-forecutter case.

In addition to the original relationship between C_d and D_{10} [2] additional lines have been added showing the relationship determined during this study with and without the forecutter for medium dense sand. The additional lines show that the relationship between permeability and C_d does not increase at the same rate with permeability as previously proposed and that the addition of the forecutter reduces the magnitude of C_d with reducing permeability as suggested in Fig. 8. The forecutter therefore is more effective at reducing rate effects in fine and silty sand than in medium sand and apparently of no significant value in coarse sands. It should be noted that in the original data used by Cathie and Wintgens [2] there was considerable grouping of data points around the lower limit of their envelope between D_{10} = 0.05 and 0.1 mm. Based upon the results for ploughs with forecutter presented here it suggests that Cathie and Wintgens [2] data set may have included ploughs both with and without forecutters but the effects of the different arrangements were not identified in this earlier study.

Based upon Fig. 12 it is tentatively proposed that when ploughing without a forecutter through medium dense sand the average dynamic resistance coefficient, C_d can be found by:

$$C_d = 0.003 \times D_{10}^{-1.931} \tag{3}$$

When ploughing with a forecutter through medium dense sand the average dynamic resistance coefficient can be found by

$$C_d = 0.007 \times D_{10}^{-1.277} \tag{4}$$

Cathie and Wintgens [2] developed the form of rate dependant component in Eq. (1) due to difficulties in obtaining appropriate values of permeability (k) and one dimensional Young's modulus (E'_0) required to determine the coefficient of consolidation (c_v). If such information could be routinely incorporated in the specification of geotechnical investigation and laboratory testing then velocity could be represented in a more appropriate-dimensionless form that allows insights into the underlying mechanisms of the rate effect behaviour [3]:

$$V = \frac{vD\,[\Delta e/1 + e_0]}{c_v} \tag{5}$$

where [$\Delta e/1 + e_0$] is the volumetric strain which is used to reflect the varying influence of dilation due to the varying relative density encountered during ploughing. Cathie and Wintgens [2] referred to this as the dilation potential (s). Lauder et al. [15] have previously shown that this form of velocity normalisation to be appropriate for model plough testing and have proposed a simplified method of determining s base upon low effective stress direct shear box testing.

It is also proposed that the form of rate correction may be more appropriate as a multiplicative correction (rather than the additive one in Eq. (1)) similar in form to that proposed by Randolph et al. [16] for the modelling of pipelines laid on the seabed surface. As the results from Fig. 11 show that the rate of ploughing has the potential to increase the effective stress in the soil and thus enhance the static components, particularly the resistance associated with passive term, although potentially less so at the skid interface contact. This is further supported by Lauder et al. [15] who showed that the rate effect was better described by D^3 rather than D^2 as proposed by Cathie and Wintgens [2]. Thus a more appropriate form of Eq. (1) would be

$$F = \left(C_w W' + C_s \gamma' D^3\right)\left(1 + C_{dn}\frac{svD}{c_v}\right) \tag{6}$$

where C_{dn} is a non-dimensional form of rate effect coefficient.

Figs. 13 and 14 show the dimensionless form of rate effect determined from model plough testing in the three test sands with and without the forecutter attachment. The coefficient of consolidation was determined using E'_0 and k selected at appropriate relative density and effective stress levels for each individual test. The normalised tow force is determined by dividing the steady state tow force (F) by the 'static' component of the tow force (or zero velocity tow force, $F_{v=0}$), for which there is no rate effect. In both cases the model generally appears to give a good fit to the model data although there appears to be some scatter associated with the tests in very dense HST50. This may be as a result of significant dilation associated with the very dense sand which is not adequately captured by the representation of dilatancy potential. It is also encouraging to note that the ratio of the rate effect coefficient included in Eqs. (7) and (8) is of a similar order to the pore pressure reduction seen in Fig. 11.

Based upon Fig. 13 it is tentatively proposed that when ploughing without a forecutter through medium dense sand the rate effect behaviour can be represented by:

$$\left(\frac{F}{F_{v=0}}\right) - 1 = 20.4\frac{svD}{c_v} \tag{7}$$

When ploughing with a forecutter (Fig. 14) through medium dense sand the rate effect behaviour can be represented by:

$$\left(\frac{F}{F_{v=0}}\right) - 1 = 9.8\frac{svD}{c_v} \tag{8}$$

To allow these general rules to be extended further a greater range of soils would be required with permeability spanning a wider range

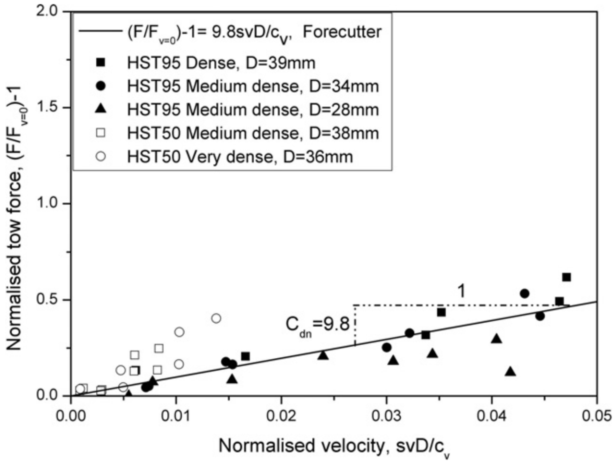

Fig. 14. Dimensionless form of the rate effect behaviour shown for the forecutter case.

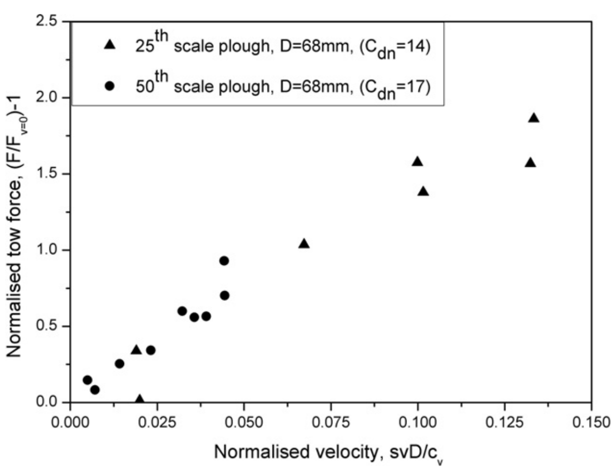

Fig. 15. Comparison of rate effects during ploughing tests performed at 50th and 25th scale (no forecutter, HST95, D_r = 53%).

than those tested here. Full relationships for medium dense to very dense sand have not been proposed as less tests were carried out in these conditions for the lowest permeability soil (Redhill110).

As in the case of the static or dry tests scaling must also be considered in the derivation of C_d and C_{dn} from model plough tests. Fig. 15 presents normalised tow forces found during 50th scale and 25th scale ploughing tests. It can be seen that over the velocities associated with the 50th scale tests (0–240 m/h) there is good agreement at both scales but there appears to be some non-linearity in the 25th scale tests (>250 m/h). Further tests would be required to verify the adequacy of scaling for the 50th scale tests where these are undertaken at higher speeds.

5.2. Identification of scenarios for beneficial forecutter use

Although the forecutter appears to be effective at reducing the magnitude of the rate effect parameter in fine and silty sands it has previously been shown that the forecutter results in the need to use an increased value of C_s. Eqs. (1) and (6) can be re-arranged in terms of velocity to allow the assessment of forecutter installation on full-scale (or prototype) ploughing progress rates using appropriate model scale parameters determined in this study (C_w, C_s, C_d or C_{dn}). Fig. 16 shows the average plough velocities calculated at various relative densities for the medium sand (HST50) where the maximum tow force available to pull the plough (bollard pull) was assumed to be 200 tonnes and the plough submerged weight was taken as 43.2 tonnes (as supplied by the plough operator).

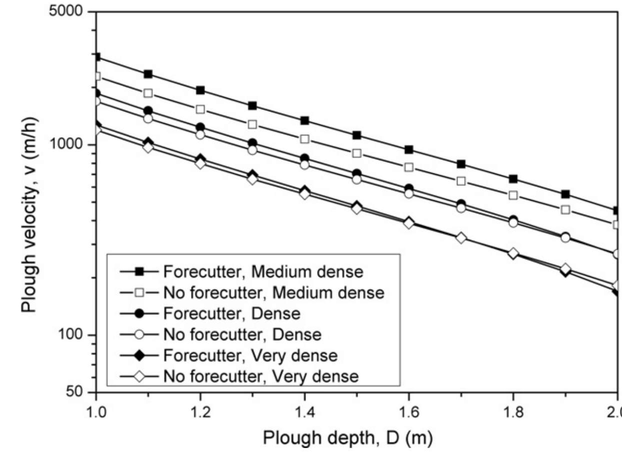

Fig. 16. Variation of average plough velocity with increasing trench depth determined for forecutter and no forecutter cases in medium sand (HST50, prototype scale).

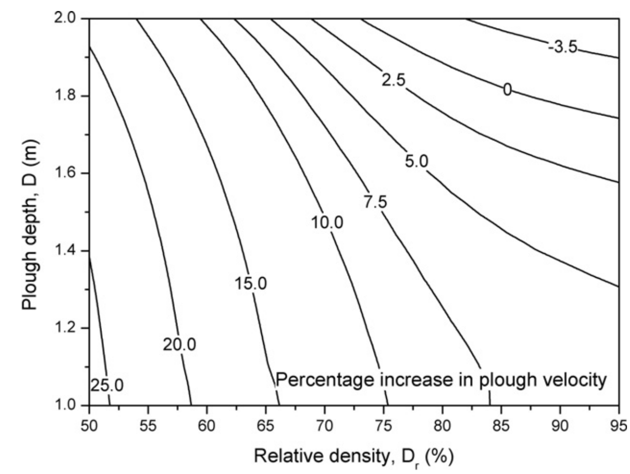

Fig. 17. The influence of plough depth and relative density on the percentage increase in plough velocity with forecutter inclusion in medium sand (HST50, 200 tonne bollard pull).

It is apparent in the medium sand (higher permeability and compressibility) that the forecutter is resulting in velocities lower than those achieved without the forecutter at deeper plough depths, in dense to very dense sand. This is a result of the increased influence of the passive component of resistance due to increased soil density, C_s and the significant effect of plough depth (D^3). Even at the reduced plough depths there is little apparent benefit of the forecutter at the higher densities. The results from Fig. 16 are summarised in Fig. 17 as a contour plot of average percentage increase in plough velocity calculated relative to the velocity where no forecutter was incorporated.

It is clear that incorporating a forecutter in medium sand would only prove a cost effective benefit in medium dense soils (or lower density) at depths below 1.65 m. This is assuming that a 10–12% increase in plough velocity would offset forecutter installation costs.

In contrast, Fig. 18 shows that the inclusion of a forecutter in fine sand (lower permeability and compressibility) has a significant benefit at all depths and relative densities. The behaviour seen in the fine sand is the opposite of that seen in the medium sand where the greatest increases in velocity performance are achieved at the higher relative densities. It should be noted though that due to the increased rate effects in the lower permeability fine sand the maximum velocities shown in Fig. 18 are lower than the lowest velocities for the higher permeability medium sand shown in Fig. 16.

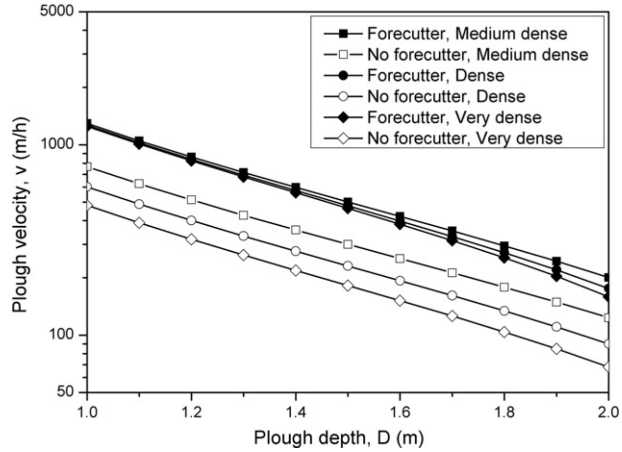

Fig. 18. Variation of average plough velocity with increasing trench depth determined for forecutter and no-forecutter cases in fine sand (HST95, prototype scale).

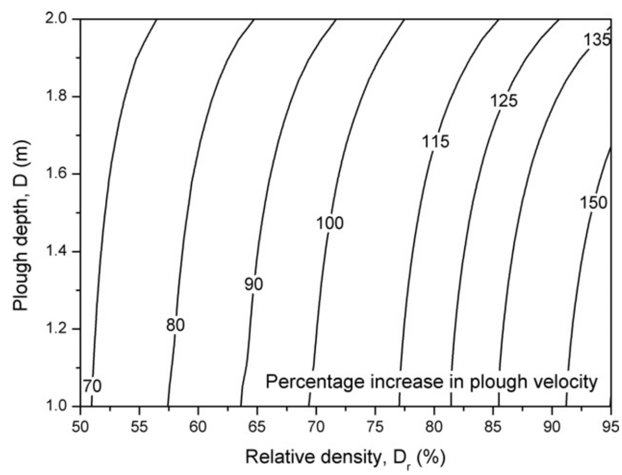

Fig. 19. The influence of plough depth and relative density on the percentage increase in plough velocity with forecutter inclusion in medium sand (HST95, 200 tonne bollard pull).

In reality a pipeline route may encounter soils of varying permeability and relative density, i.e. zones where a forecutter is a significant benefit and others where it is a hindrance. Through the use of figures similar to Figs. 16–19 it is possible to determine if including a forecutter is an overall benefit or not based upon the anticipated soil conditions. For instance a route composed predominantly of medium to coarse sand would not be suitable for forecutter use whereas one that predominantly consisted of silty or fine sand would. Some level of conservatism may be required during this process though depending upon the accuracy and linear frequency of insitu testing and/or soil characterisation.

6. Conclusions

The decision to incorporate a forecutter on a pipeline plough has the potential to significantly reduce towing forces, or for a fixed bollard pull increase ploughing speeds. Currently there is limited and conflicting evidence in the technical literature as to the advantages or disadvantages of incorporating a forecutter.

Laboratory testing of 1/50th scale model pipeline ploughs has shown that the passive pressure coefficient (C_s) does not appear to vary with relative density to the same degree recommended by a previous study [2]. Also, the forecutter increases the magnitude of the C_s term which reflects an increase in the passive resistance to ploughing. In terms of this study it is clear that incorporating a forecutter leads to an increase in the “static” force component of between 5 and 19% depending on relative density, plough depth and soil type. This increase is a negative impact of incorporating the forecutter which needs to be offset by reductions in the rate effect component of ploughing resistance.

In saturated soils the forecutter acts to reduce the rate effect component of plough tow force. Monitoring of pore pressure change below the advancing plough showed reduced pressure reductions where a forecutter was incorporated suggesting that the forecutter may act to reduce the drainage path length of the sheared soil around the main share. The forecutter reduced the rate effect in both fine sand (low permeability and compressibility) and to a lesser extent in medium sand (higher permeability and compressibility). In the higher permeability soil where the rate effects were less significant the inclusion of the forecutter reduces the rate effect but increases the overall tow force to an extent that inclusion had a negative effect over the range of velocities investigated. Current models used to describe the rate effect based upon soil particle size do not acknowledge the reduced rate effects due to forecutter inclusion.

A new model that allows the rate effect to be determined in a dimensionless form which incorporates the effects of soil compressibility was also verified against the model testing. This approach was found to give encouraging performance in predicting rate effects for both the forecutter and no-forcutter cases in medium dense sand. To allow use of such a form of analysis soil stiffness, permeability and dilation potential need to be routinely assessed as part of the pipeline route ground investigation.

The decision to include a forecutter needs to be made with regard to the ploughing conditions, specifically contract trench depth and more importantly the permeability or compressibility of the soil. In fine and silty sands (lower permeability and compressibility) incorporating a forecutter would seem highly beneficial at all ploughing depths and soil densities but in medium sand (higher permeability and compressibility) the benefits of incorporation are limited to an operating window at shallower trench depth and lower relative density. For practical purposes the decision will need to be made through optimisation of the anticipated ploughing velocities depending on the level of variability of soil permeability/compressibility (and to a lesser extent relative density) encountered along the proposed pipeline route.

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